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Figure of merit for magneto-optical media based on the dielectric tensor

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A figure of merit is derived for the magneto-optical media used in erasable optical data storage. It is shown that the ratio of the useful signal generated by the polar Kerr effect to the incident laser power is always below the figure of merit, but the figure can be approached if the magneto-optic medium is embedded in a proper multilayer structure.

Readout in magneto-optical data storage is achieved through the magneto-optic Kerr or Faraday effect. Both phenomena can be described in terms of the medium's dielectric tensor which has the following structure[1,2]:

$$\epsilon = \begin{pmatrix} \epsilon & i\epsilon' & 0 \\ -i\epsilon' & \epsilon & 0 \\ 0 & 0 & \epsilon \end{pmatrix}. \qquad (1)$$

A linearly polarized beam, traveling perpendicular to the plane of the medium, can be decomposed into right and left circularly polarized waves; the refractive index for these waves is given by

$$n^{\pm} = (\epsilon \pm \epsilon')^{1/2}. \qquad (2)$$

Using Maxwell's equations for a plane wave incident on a multilayer structure[3,4] it is possible to obtain the magneto-optically induced component of polarization in both reflection and transmission. Assuming that E_i and E_r represent the amplitudes of the incident and reflected waves, respectively, we can write

$$r_\perp = E_r^\perp / E_i = 0.5(r^+ - r^-). \qquad (3)$$

In the above equation we have assumed that the incident beam is linearly polarized. $E_r^\perp$ is the component of the reflected beam which is perpendicular to the direction of incident polarization, while $r^\pm$ are amplitude reflectivities for the right and left circularly polarized light.

Now consider a thin film of a magneto-optic material deposited on a substrate of refractive index n_s and illuminated from the air side as shown in Fig. 1. If the film thickness Δ is much less than the vacuum wavelength λ_0 of light we can show that

$$|r_\perp| = (4\pi\Delta/\lambda_0)\, |\epsilon'|/|1+n_s|^2. \qquad (4)$$

$|r_\perp|$ is the amplitude reflectivity for the magneto-optically generated component of polarization. In deriving Eq. (4) we have ignored the effect of the bottom side of the substrate, keeping it, in effect, at infinity.

Next, consider the absorbed power in the magneto-optic layer. If we ignore the off-diagonal element of the dielectric tensor and treat the magneto-optic layer as a simple metallic layer with complex refractive index $n = \sqrt{\epsilon}$, the Poynting theorem for the structure in Fig. 1 yields

$$\frac{P_{\rm abs}}{P_{\rm inc}} = \frac{8\pi\Delta}{\lambda_0} \frac{\mathrm{Im}(\epsilon)}{|1+n_s|^2}, \qquad (5)$$

where $P_{\rm inc}$ is the incident beam power and $P_{\rm abs}$ is the power absorbed by the magneto-optic layer. The implicit assumptions here are $\Delta \ll \lambda_0$ and $\epsilon' \ll \epsilon$. Comparing Eq. (4) with Eq. (5) we arrive at the following conclusion:

$$|r_\perp| = [|\epsilon'|/2\,\mathrm{Im}(\epsilon)]\,(P_{\rm abs}/P_{\rm inc}). \qquad (6)$$

Although the above discussion has been confined to a thin film on an arbitrary substrate, the final result in Eq. (6) is quite general and applies to a thin magneto-optic layer in any arbitrary structure. There is an intuitive justification for this statement which becomes clear in the course of the following discussion.

Consider a multilayer structure, such as that shown in Fig. 2, where a magneto-optic film of thickness t_f exists

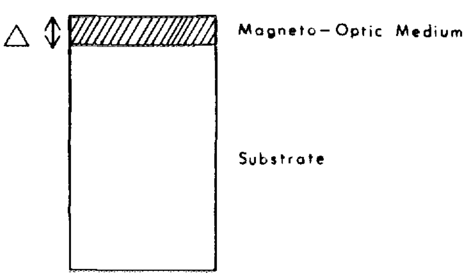

FIG. 1. Thin magneto-optic film on substrate. The medium of incidence is air and the incident beam is linearly polarized.

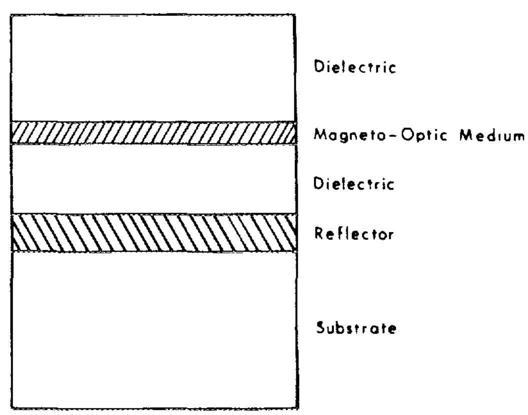

FIG. 2. Multilayer structure with one magneto-optic layer. The other layers are metal or dielectric.

TABLE I. Multilayer structures for which the function $|r_\perp| P_{inc}/P_{abs}$ vs the magneto-optic film thickness t_f is plotted in Fig. 3.

Structure	Substrate refractive index	Layer 1	Layer 2	Layer 3	Layer 4	Incidence medium
a	$n = 3.67 + i3.86$	TbFe	...	...	...	Air
b_1	$n = 1.5$	TbFe	...	...	...	Air
b_2	$n = 1.5$	TbFe	300 Å, $n = 3.67 + i3.86$	...	...	Air
b_3	$n = 1.5$	TbFe	1000 Å, $n = 1.5$	...	...	Air
b_4	$n = 1.5$	TbFe	1000 Å, $n = 1.5$	300 Å, Al	...	Air
b_5	$n = 1.5$	TbFe	...	...	...	$n = 1.5$
c_1	$n = 1.5$	1000 Å, Al	1000 Å, $n = 1.5$	TbFe	...	Air
c_2	$n = 1.5$	1000 Å, Al	750 Å, $n = 2.0$	TbFe	1000 Å, $n = 2.0$	Air

among several layers of various nonmagnetic metals and dielectrics. To be specific, we choose the magneto-optic medium to be an amorphous alloy of TbFe with $\epsilon = -1.4 + i28.3$ and $\epsilon' = 0.12 + i0.57$ at $\lambda_0 = 820$ nm. The various structures that are considered are listed in Table I. Figure 3 shows plots of $|r_\perp| P_{inc}/P_{abs}$ vs t_f for these structures. Structure a is TbFe on matched substrate, i.e., the refractive index of the substrates is $n_s = \sqrt{\epsilon}$ where ϵ is the diagonal element of the dielectric tensor for TbFe. Curve (a) in Fig. 3 corresponds to this structure. It is observed that for small t_f the function approaches the value of $|\epsilon'|/2\,\mathrm{Im}(\epsilon) = 1.03 \times 10^{-2}$ as indicated by Eq. (6). As t_f increases the function decreases indicating that the magneto-optically generated components of polarization throughout the TbFe layer are not in phase.

Structures b_1 through b_5 in Table I all share the same characteristic curve (b) in Fig. 3. The common feature of these structures is a TbFe layer that is directly deposited on a glass substrate; the differences are in the coating layers and in the refractive index of the medium of incidence. At small t_f the curve obeys Eq. (6) and thus coincides with curve (a) in this region, but as t_f increases the effect of the substrate becomes apparent. Initially the reflection at the film-substrate interface creates a magneto-optic signal that is in phase with the signal from the surface and thus enhances $r_\perp$, but at larger t_f the opposite occurs (destructive interference) and the signal drops, bringing curve (b) well below curve (a). Eventually at very large t_f the light no longer sees the substrate and thus the two curves coincide again.

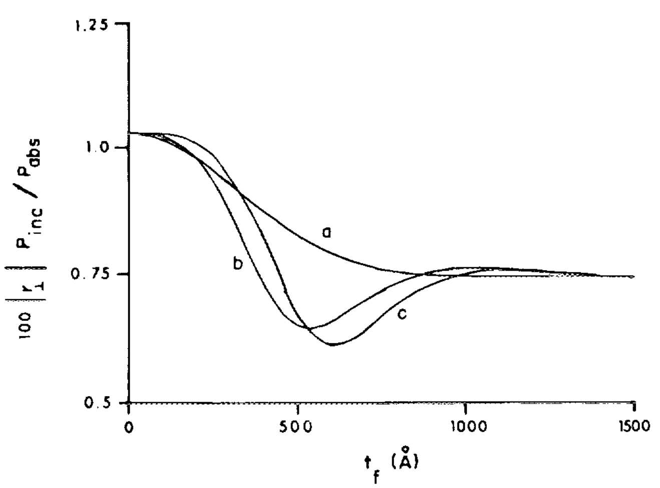

FIG. 3. Performance curves for the structures listed in Table I. The abscissa is the thickness of the TbFe layer.

Finally, structures c_1 and c_2 in Table I share the curve (c) in Fig. 3. These structure consist of a glass substrate, overcoated with 1000 Å of aluminum and a layer of transparent dielectric under the TbFe layer. Structure c_2 is overcoated with another dielectric layer and the medium of incidence in both cases is air. Note that the optical thickness of the intermediate dielectric layer is the same for c_1 and c_2. It is observed that when $t_f \to 0$ the curve approaches the limit of Eq. (6). Also, as in curve (b), the constructive and destructive interferences between the signals generated at the top and the bottom of the TbFe layer are responsible for the enhancement of the curve at small t_f and its depression at larger t_f. The larger reflectivity at the substrate in the case of curve (c) accounts for its differences with the curve (b).

From the above discussion we conjecture that the value of $|r|$ given by Eq. (6) is the maximum possible value one can obtain from a given medium. The fact that P_{abs} is, in general, less than or equal to P_{inc} leads to the following conclusion:

$$|r_\perp| \leqslant |\epsilon'|/2\,\mathrm{Im}(\epsilon). \quad (7)$$

The upper bound in Eq. (7) is achieved if two conditions are satisfied: (i) all the incident light is absorbed by the magneto-optic medium and (ii) the magneto-optically induced components of polarization at various depths within the active layer are added in phase. Table II lists several structures of varying complexity and compares their performance against the upper bound of Eq. (7). Note in particular that the structure in the last row can achieve as much as 93% of the maximum possible magneto-optical signal.

It is reasonable to expect that the upper bound in Eq. (7) should also apply to the Faraday effect where instead of $r_\perp$ one should use the amplitude transmission coefficient $t_\perp$. Justification of this conjecture is much more difficult than the previous one, but all numerical calculations indicate its validity, namely,

$$|t_\perp| = |E_t^\perp/E_i| \leqslant |\epsilon'|/2\,\mathrm{Im}(\epsilon). \quad (8)$$

In fact, for the TbFe medium of the previous examples, the

TABLE II. Single and multilayer structures and their performance parameter $|r_\perp|$ as compared to the figure of merit of the magneto-optic medium. The figure of merit, $|r_\perp|_{max}$, is the maximum achievable performance parameter and is given by $|\epsilon'|/2\,\mathrm{Im}(\epsilon)$. The last column gives the reflectivity, which is the percentage of incident power reflected from the structure.

Substrate	Layer 1	Layer 2	Layer 3	$\lvert r_\perp\rvert/\lvert r_\perp\rvert_{max}$	R
Glass	5000 Å,TbFe	...	...	0.29	60%
Glass	100 Å,TbFe	...	...	0.39	33%
Glass	750 Å,TbFe	850 Å,n = 2	...	0.60	13%
Glass	220 Å,TbFe	900 Å,n = 2	...	0.69	5%
Aluminum	1900 Å,n = 2	500 Å,TbFe	800 Å,n = 2	0.76	12%
Aluminum	750 Å,n = 2	200 Å,TbFe	1250 Å,n = 2	0.80	16%
Aluminum	750 Å,n = 2	200 Å,TbFe	1000 Å,n = 2	0.93	2%

largest value of $|t_\perp|$ we could find is only 60% of the upper bound.

A major difference between the Kerr and the Faraday effects is that in the latter case the function $|t_\perp|P_{inc}/P_{abs}$ is no longer bounded by the figure of merit. This shows that, under certain conditions, the Faraday effect is larger than the Kerr effect for a given amount of absorbed power. The ratio of the absorbed power to the incident power in such cases, however, is such that the upper bound of Eq. (8) is always satisfied.

In conclusion, we have found a figure of merit based on the dielectric tensor of the magneto-optic media. This figure of merit places an upper limit on the useful magneto-optic signal ($r_\perp$ or $t_\perp$) that can be obtained from a given medium. Moreover, we have shown that the above limit is approached in properly designed multilayer structures.

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